



European  
Commission

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 801055.*



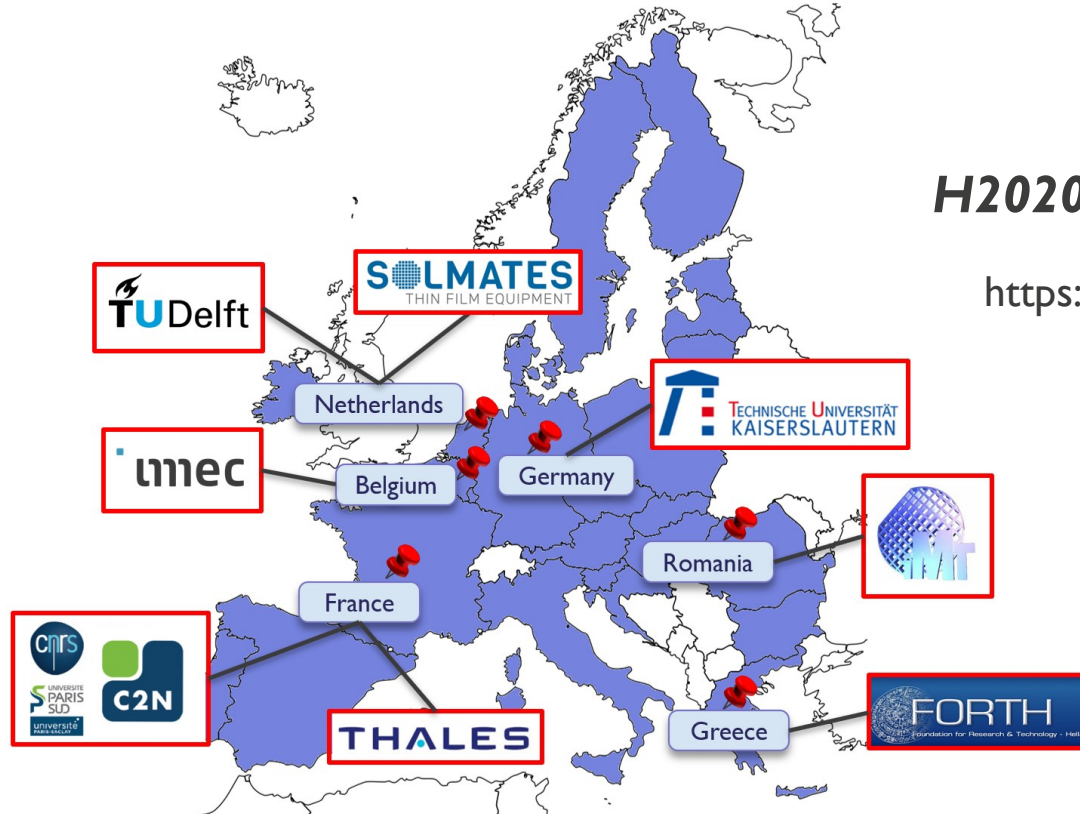
**umec**

The CHIRON concept – Computing with spin waves

Christoph Adelmann

*CHIRON workshop – Heraklion, Crete - 27.04.2022*

# The CHIRON project

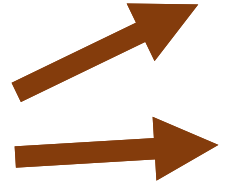
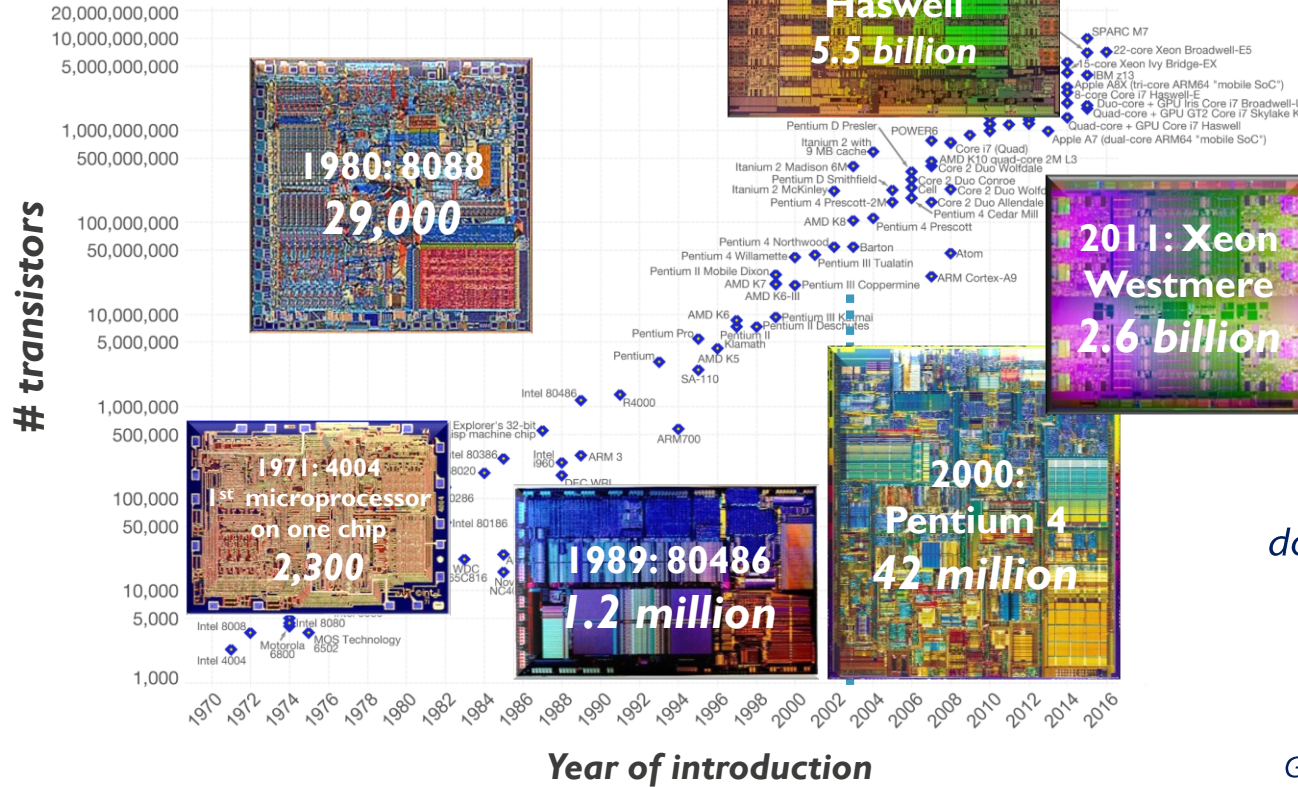


**H2020 FET-OPEN project**

<https://www.chiron-h2020.eu/>

**2018 to 2022**

# Moore's law



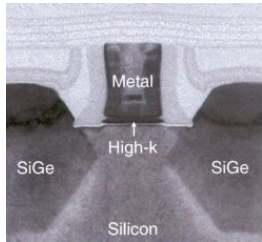
*The number of transistors doubles every new technology node while area and cost remain the same.*

G. Moore, 1965

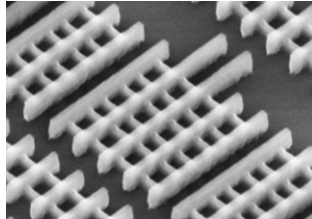


# Transistor vs. logic gate scaling

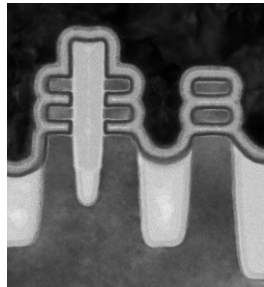
## Transistor scaling



45 nm HKMG  
planar transistor

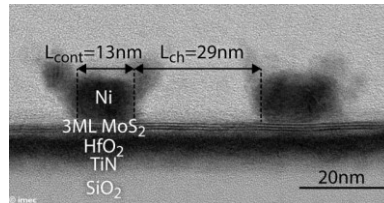


22 nm FinFET



3 nm gate-all-around and  
forksheet FET

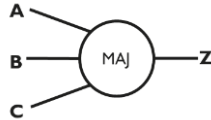
2D transistor



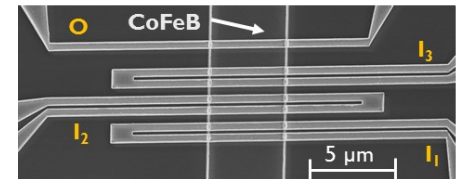
## Logic gate/building block scaling

### Scaling of logic building blocks instead of transistors

- Example: majority gates
- Non-charge (non-CMOS) approaches become competitive




Truth Table	A	B	C	Z	AND
	0	0	0	0	
	0	0	1	0	
	0	1	0	0	
	0	1	1	1	
1	0	0	0	OR	
1	0	1	1		
1	1	0	1		
1	1	1	1		

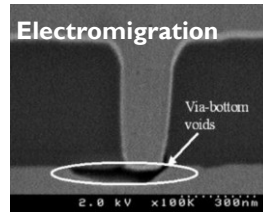


Spin-wave MAJ gate realized  
by CHIRON

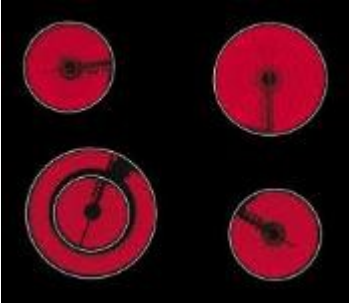
# Power consumption of CMOS circuits

**Today, power dissipation and consumption is the main limiting factor for microelectronic devices**

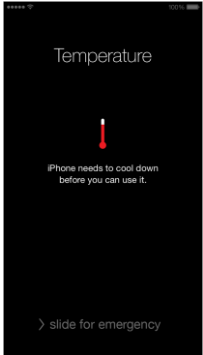
- Circuit delay: clock frequency limited by active power
- Battery lifetime 
- Reliability – Power and current density
- User experience – Surface temperature
- Server cooling cost



Current high performance processors:  
**>50 W/cm<sup>2</sup>**



**Need for lower power electronics!**

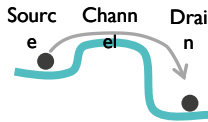


# Potential of spintronic logic



## LOW POWER COMPUTATION

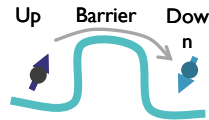
### Electronic Switch



$$E_{CHARGE} = NeV \sim 4000KT$$

$$N = 200 \text{ electrons}$$

### Spintronic Switch

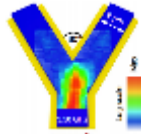


$$E_{SPIN} = \frac{\mu_0 V M_s H_k}{2} \sim 60KT$$



## FUNCTIONAL SCALING

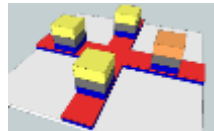
### Spin Waves



### All-spin logic



### Spin Torque Majority Gate



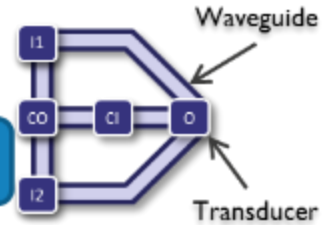
## COMPACT CIRCUITS

CMOS circuit  
25 transistors



Majority Gate Computing Circuit  
5 transducers & 4 wave-guides

I = Input  
O = Output  
CI/CO = Carry in/out

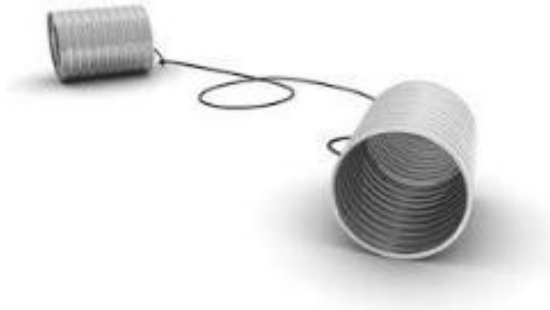


# What is wave computing?

Basic building blocks of wave computing



Wave emitter  
(Transducer)



Waveguide for propagation  
and interference

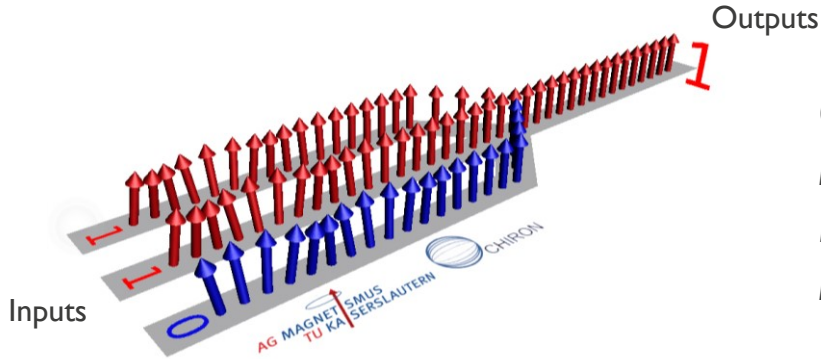


Wave detector  
(Transducer)

When wave computing circuits are integrated alongside CMOS, the emitters and detectors have to be **transducers** between the wave and the electric domains.

# How does wave computation work?

Basic principle of (spin wave) majority gate



*Computation by interference.  
Natural logic gate:  
majority gate.*

I1	I2	I3	O
0	0	0	0
0	0	1	0
0	1	1	1
1	1	1	1

**Output phase after interference is equal to the majority of input phases.**

*In wave computing, information is coded in the phase or the amplitude of the wave.*

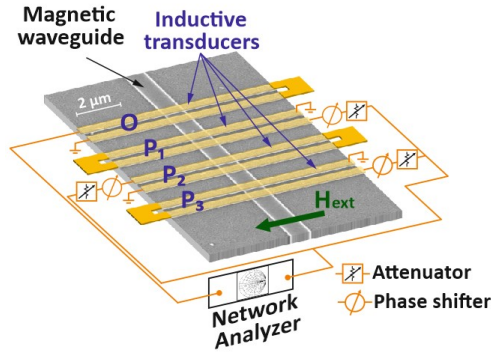
*A. Mahmoud, et al., J. Appl. Phys. **128**, 161101 (2020).*

*Different waves and physical state variables can be used.*

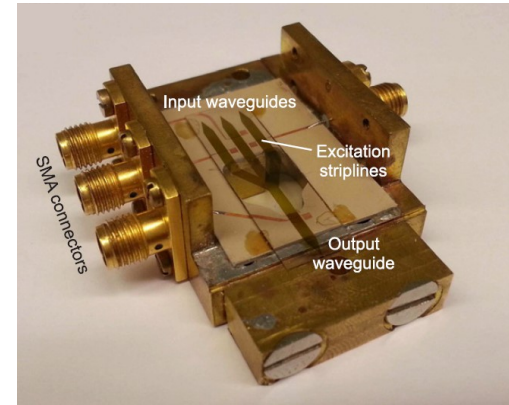
WAVE	STATE VARIABLE	PROPERTIES
Spin wave	Magnetization/spin	GHz frequency, a few $\mu\text{m}$ propagation length
Plasmon (SPP)	Electric field	THz frequency, 10s of $\mu\text{m}$ propagation length
Ultrasound wave	Displacement/strain	MHz to GHz frequency, $\mu\text{m}$ to mm propagation length

# Spin-wave majority gates

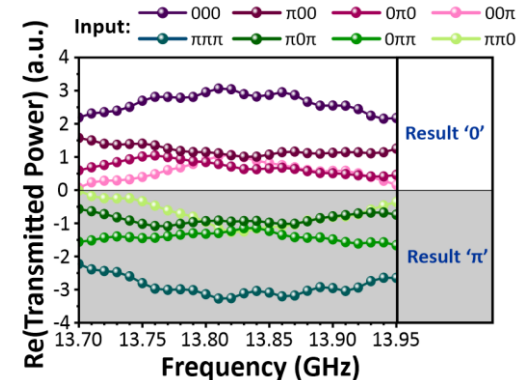
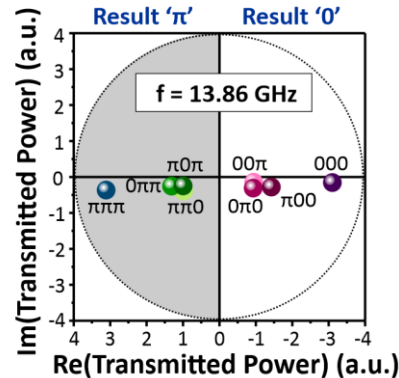
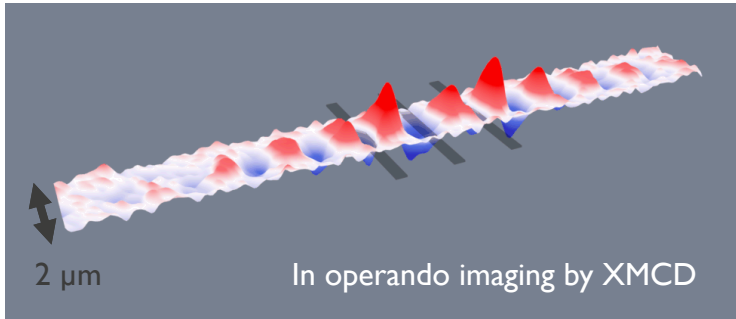
## CHIRON realization with sub- $\mu\text{m}$ dimensions



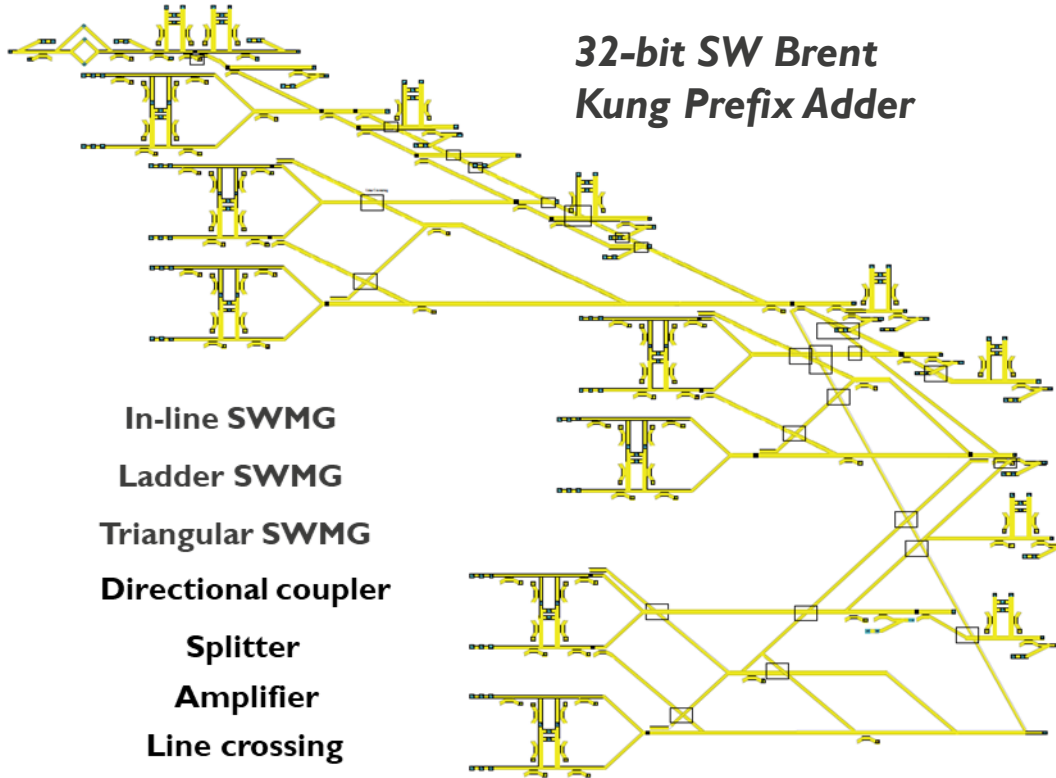
G. Talmelli, *et al.*,  
Reconfigurable submicrometer  
spin-wave majority gate with  
electrical transducers, *Sci. Adv.*  
**6** (2020) eabb4042.



Prototype: T. Fischer, *et al.*, Experimental prototype of  
a spin-wave majority gate, *Appl. Phys. Lett.* **110** (2017)  
152401



# Spin wave circuits



***CHIRON* concept for spin  
wave circuit design  
developed**

(Inline) MAJ gates and inverters are not sufficient for the design of more complex circuits

- Different MAJ gate designs
- Directional couplers
- Amplifiers
- Routing crosses

However, this is not yet a  
“computer”



No concept of a computer (or even a full processor, including memory) based only on spin waves exist!





CHIRON proposes hybrid  
spin-wave CMOS systems.

Transducers are key!

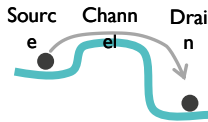


# Potential of spintronic logic



## LOW POWER COMPUTATION

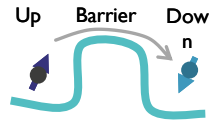
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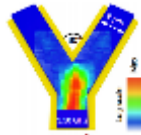


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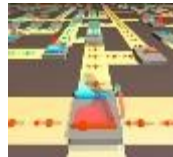


## FUNCTIONAL SCALING

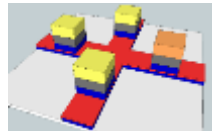
### Spin Waves



### All-spin logic



### Spin Torque Majority Gate



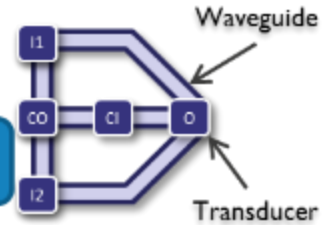
## COMPACT CIRCUITS

CMOS circuit  
25 transistors



Majority Gate Computing Circuit  
5 transducers & 4 wave-guides

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# Why voltage-based spintronics?



## Energy estimates

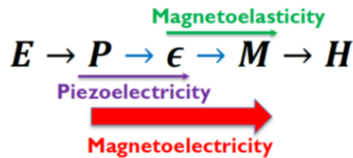
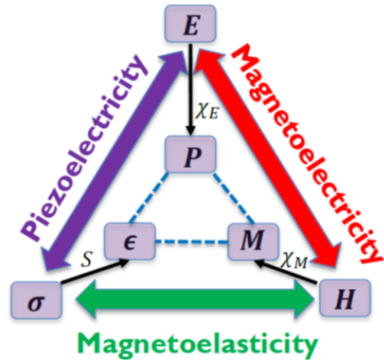
- **Spin-transfer torque:**  $E = RA \times J^2 \times A^2 \times t = 5 \Omega\mu\text{m}^2 \times (5 \times 10^6 \text{ A/cm}^2)^2 \times (10 \text{ nm})^2 \times 10 \text{ ns}$   
 $\sim 10 \text{ fj}$
- **Capacitive energy:**  $H_k = 0.1 \text{ V} \times (10 \text{ nm})^{-1} \times 10 \text{ Oe/(kV/cm)} \sim 1000 \text{ Oe}$   
 $E = \frac{1}{2} CV^2 = \frac{1}{2} \times 8.85 \times 10^{-12} \text{ F/m} \times 100 \times (10 \text{ nm})^2 \times (10 \text{ nm})^{-1} \times (0.1 \text{ V})^2$   
 $\sim 10^{-4} \text{ fj}$

*Much lower energy needed by charging a capacitor and manipulating nanomagnets by voltages than by spin transfer torque. However, full energy assessments for magnetoelectric replacement devices are often not (yet) available.*

# What are magnetoelectrics?

## Approaches to magnetoelectric coupling

### Magnetoelectric composites

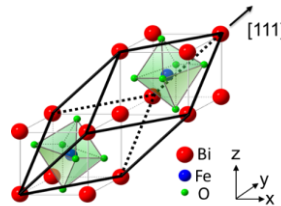


*Coupling via strain.*

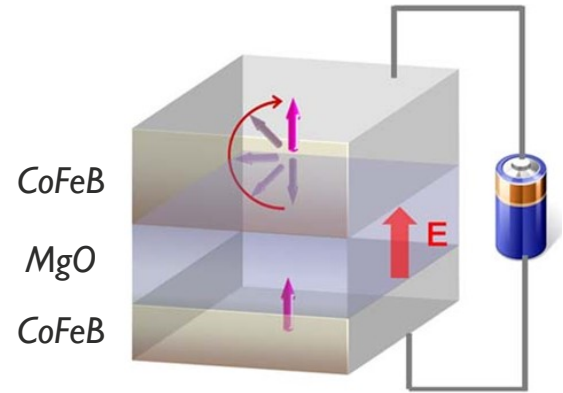
### Multiferroics

*Intrinsic coupling in materials with both ferroelectric and (anti-)ferromagnetic order.*

*Example: BiFeO<sub>3</sub>*



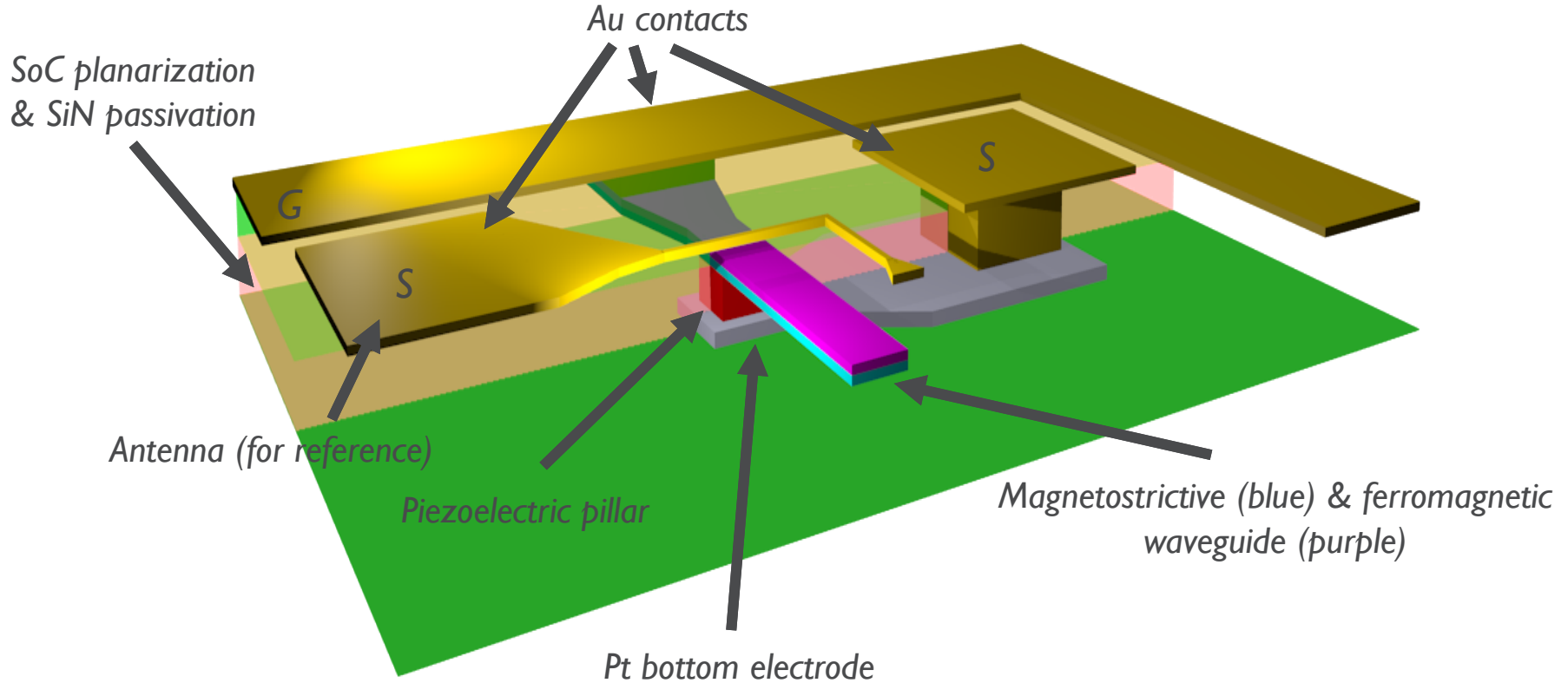
### Voltage control of magnetic anisotropy (VCMA)



*Coupling via interface charge.*

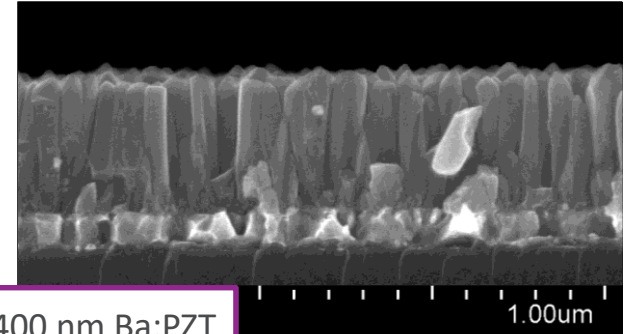
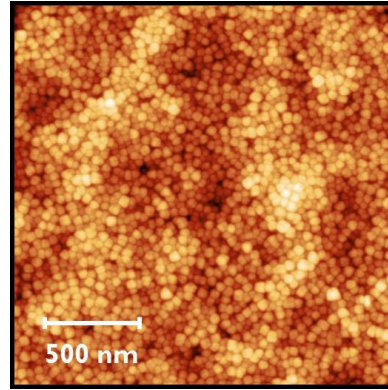
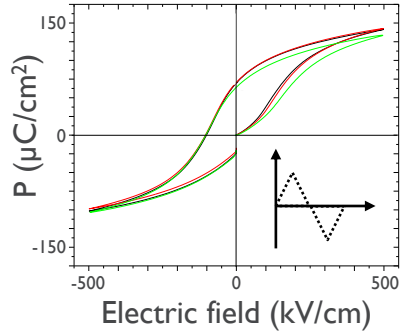
# Magnetolectric spin wave transducers

## Basic device structure



# Piezoelectric: Ba-substituted PZT

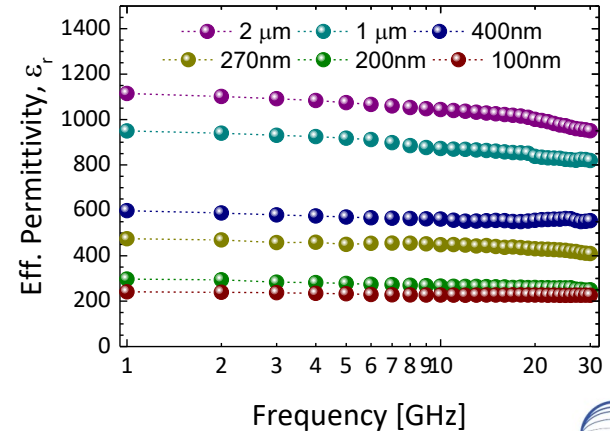
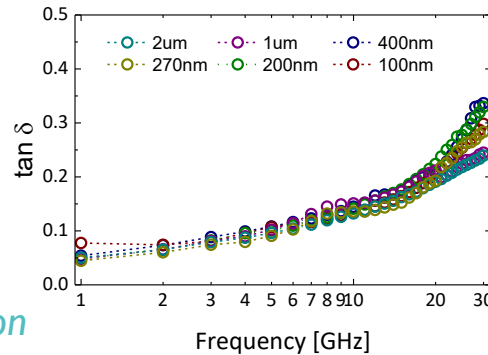
## Deposition and materials properties



*Excellent microwave dielectric properties.*



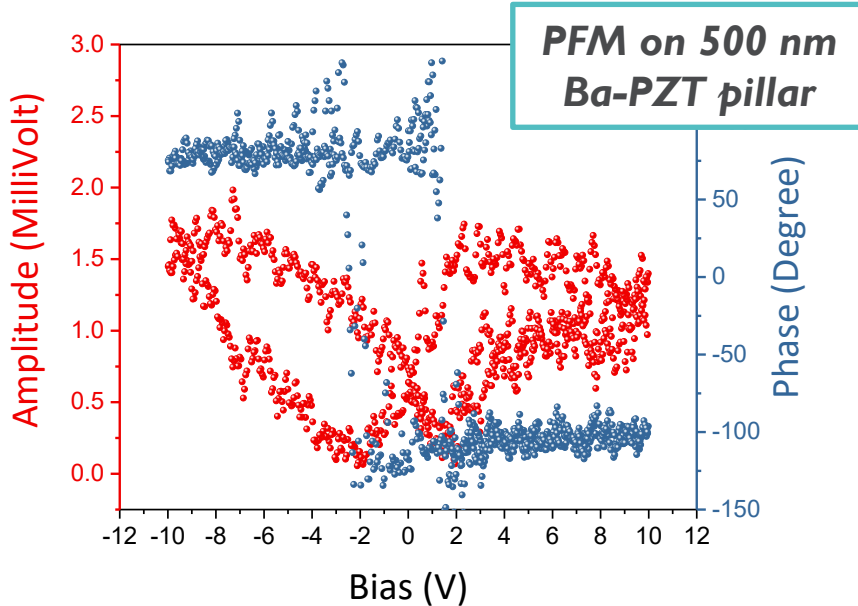
*Ba:PZT by Pulsed Laser Deposition*



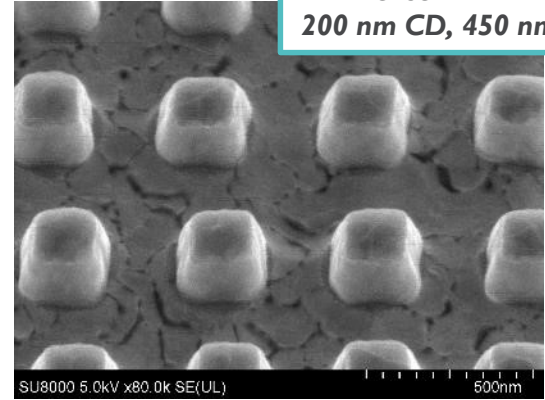
# Experimental magnetoelectric pillar transducers

## Pillar patterning

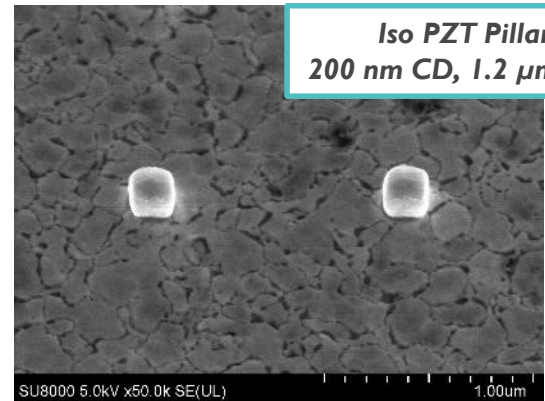
*Ba:PZT pillar patterning down to 100 nm achieved.  
PFM shows ferroelectricity in smallest structures.*



**Dense PZT Pillars**  
200 nm CD, 450 nm pitch

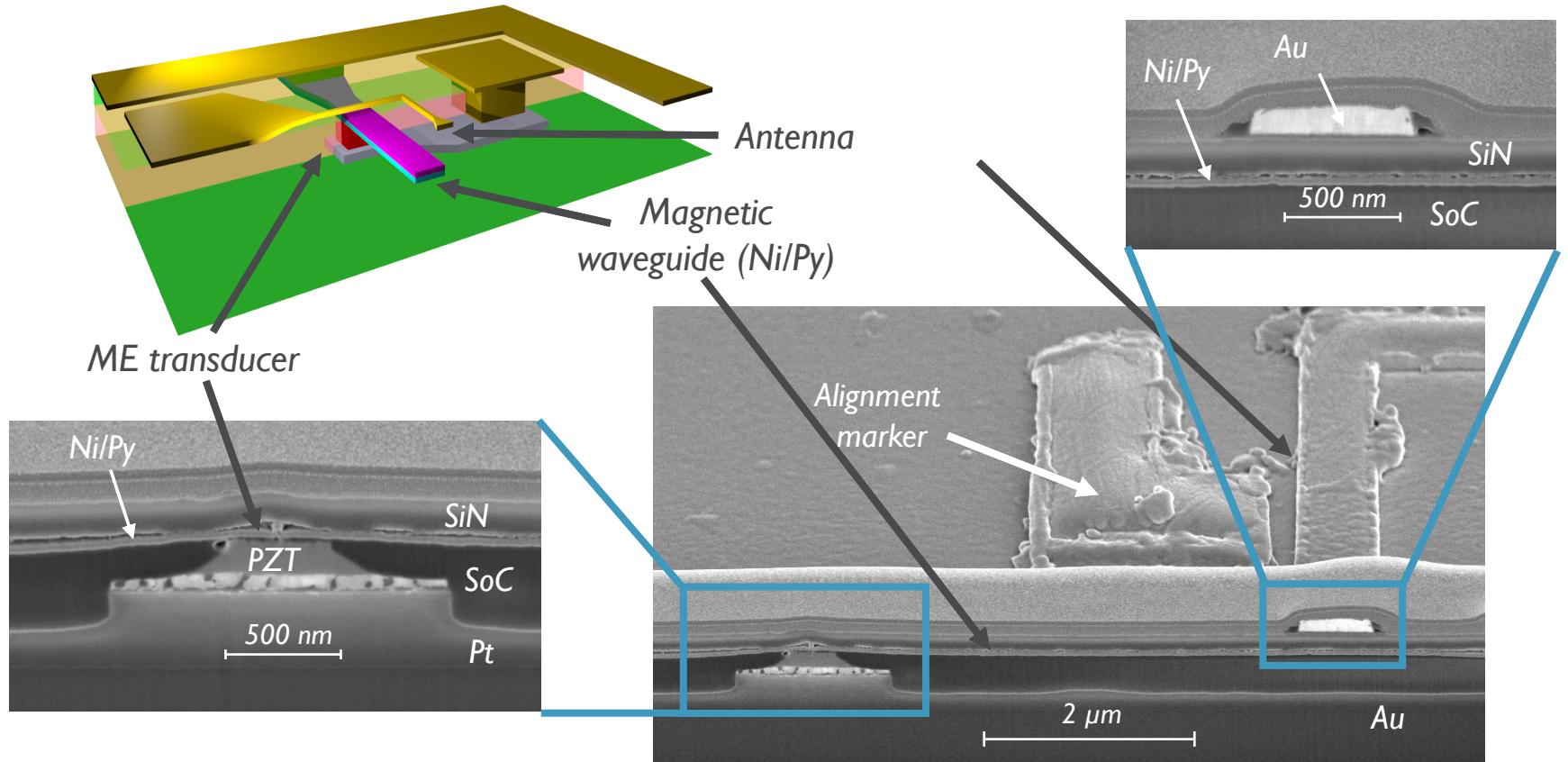


**Iso PZT Pillars**  
200 nm CD, 1.2 μm pitch



# Magnetolectric pillar transducers

## Device structure

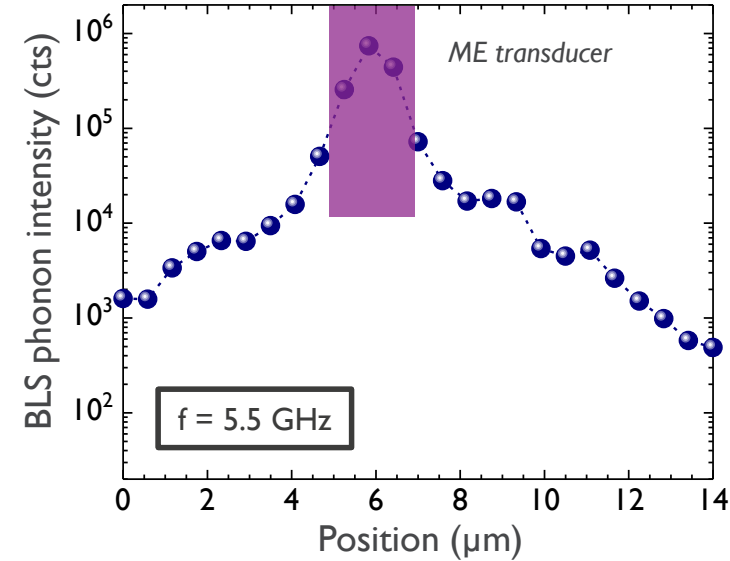
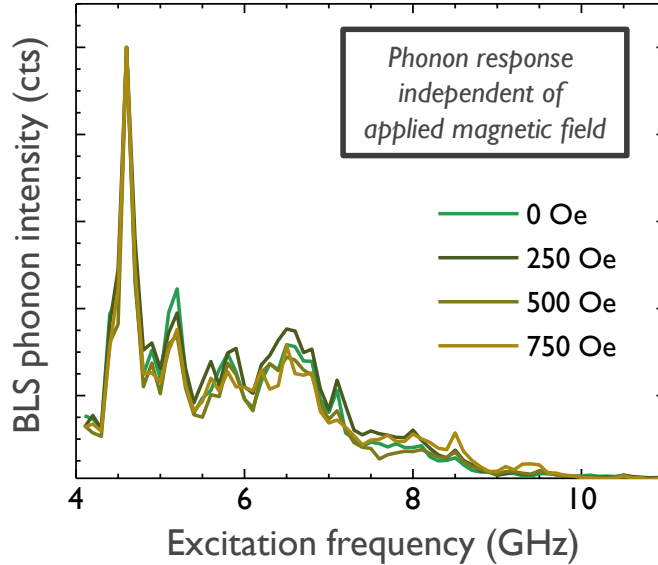
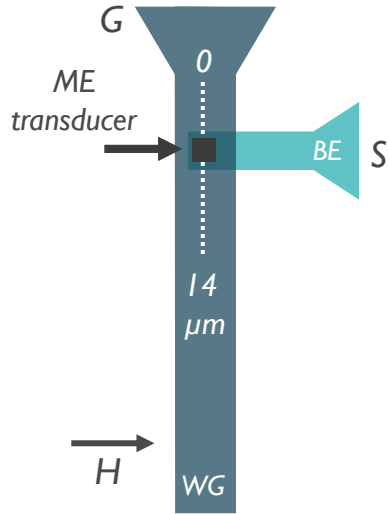


# Phonon excitation by magnetoelectric pillar transducers



Measurement by Brillouin light scattering

ME cell width:  $2\ \mu\text{m}$   
Waveguide width:  $5\ \mu\text{m}$   
Ni(25nm)/IPy(25nm)



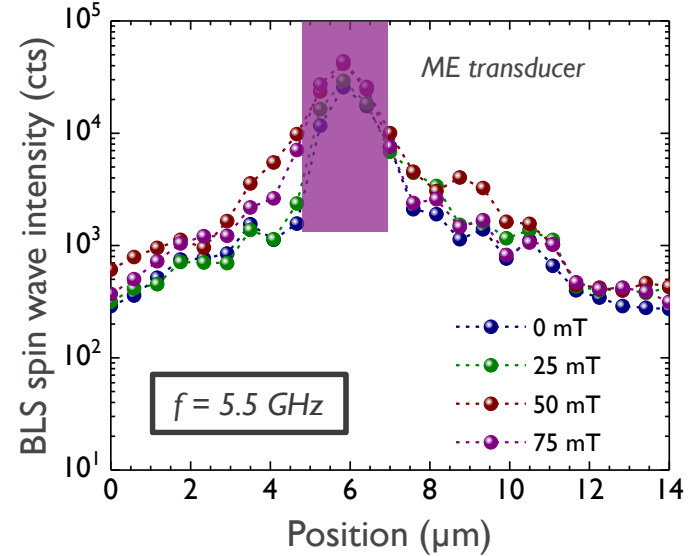
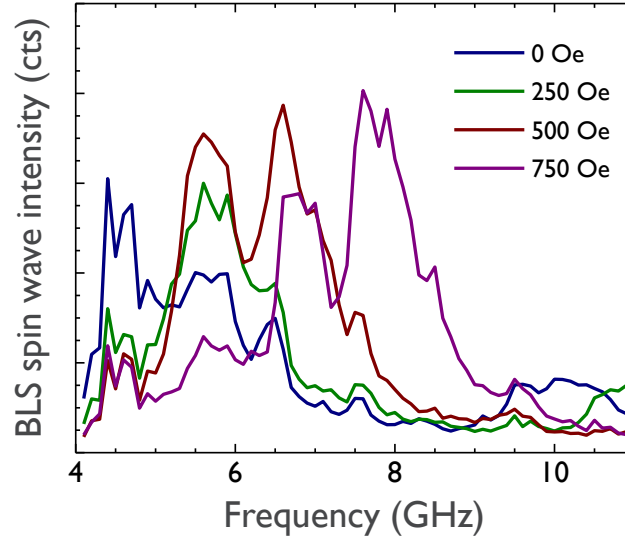
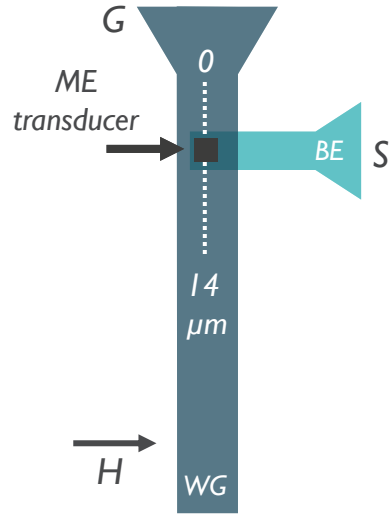
Complex phonon spectrum with large bandwidth obtained.  
Phonons propagate away from transducer with decay length of about  $2\ \mu\text{m}$ .

# Spin wave excitation by of magnetolectric pillar transducers



Measurement by Brillouin light scattering

ME cell width:  $2\ \mu\text{m}$   
Waveguide width:  $5\ \mu\text{m}$   
Ni(25nm)/IPy(25nm)



Complex spin wave spectrum shows blueshift with magnetic field according to dispersion relations. Spin waves propagate away from transducer with decay length of about  $1.5\ \mu\text{m}$ .

- CHIRON has developed spin-wave circuits based on majority gates, inverters, directional couplers, and amplifiers
- Hybrid approaches allow extension of spin wave circuits to chip level
- Magnetoelectric transducers are promising for future spintronic (logic) technologies
- First devices demonstrated. High device complexity but also highly interesting physics.



# umec

## embracing a better life



*This project has  
received funding from  
the European Union's  
Horizon 2020  
research and  
innovation programme  
under grant agreement  
No. 801055.*

